Synthetic Topological Quantum Matter
August 1-4, KITPC, Beijing

___ Ultracold atoms (experiments) (14 talks)
___ Condensed matter (7 talks)
___ Photonics (experiments) (3 talks)
___ Ultracold atoms or photonics (theory) (14 talks)

Invited speakers (alphabetic order) & Titles and abstracts of talks

1. **Monika Aidelsburger,** (Max Plank Institute / LMU, Munich, Germany)
Artificial gauge fields and topology with ultracold atoms in optical lattices
Abstract: Topological states of matter exhibit unique conductivity properties, which are particularly robust against perturbations, as e.g. discovered in the context of the integer and fractional quantum Hall effect. Ultracold atoms in optical lattices constitute promising candidates to study and find novel topological states of matter. However, since atoms are charge neutral new experimental techniques had to be developed to mimic the physics of charged particles in magnetic fields. Here, I present a method based on laser-assisted tunneling, where the motion of the atoms in the lattice is modified using additional far-detuned laser beams and static potentials. This technique enabled the realization of extremely strong artificial magnetic fields on the order of one magnetic flux quantum per lattice unit cell. In particular we implemented the Hofstadter model for a flux pi/2, whose lowest band is topologically equivalent to the lowest Landau level. The strength and distribution of the field was probed through the observation of quantum cyclotron orbits on isolated four-site square plaquettes. Additionally, we observed for the first time the spin Hall effect in an optical lattice and determined the Chern number of the lowest Hofstadter band through the observation of bulk topological currents.

2. **Nicholas P. Bigelow** (University of Rocherter, USA)
Generation of Synthetic Fields in 87Rb Bose-Einstein Condensates
Abstract: We create and analyze spin textures in spinor Bose-Einstein condensates (BECs) that correspond to two types of monopole and antimonopole structures. The first is a topological spin monopole, characterized by a radial local spin. The second has a cross-disgyration spin texture that corresponds to a radial synthetic magnetic gauge field in the vorticity of the condensate. These vortex- based spin textures are engineered by an optical Raman imprinting technique that provides precise control of the spatially dependent spin and vortex states and relative phases in the BEC. This light-matter interaction additionally generates a monopole light-induced gauge potential. Also, we deterministically create four distinct types of fractional vortices: half-quantum or Alice vortices in the spin-1 manifold and half-quantum, half-quarter, 1/3-quantum, and 2/3-quantum vortices in the spin-2 manifold. All of the spin-2 vortices are non-Abelian. Each configuration has singly quantized vortices with non-rotating cores in other spin components.

3. **Hrvoje Buljan** (University of Zagreb, Croatia)
Synthetic gauge fields in strongly interacting 1D Bose gases, and Weyl semimetals in 3D optical lattices
Abstract: We discuss two important directions of research of synthetic topological quantum matter [1]: (i) strongly interacting Bose gases in synthetic gauge fields [2], and (ii) topological phases in 3D optical lattices, more specifically Weyl semimetals in ultracold atomic gases [3]. Interacting Bose gases in synthetic magnetic fields [1] hold great potential for discovering and exploring novel topological states of matter [4], in a similar fashion as the fractional quantum Hall effect for electrons in strong magnetic

fields. Here we investigate laser assisted tunneling in a strongly interacting one-dimensional Bose gas [2] (the Tonks-Girardeau gas [5]) in optical lattices. We find that the stroboscopic dynamics of the Tonks-Girardeau gas in a continuous Wannier-Stark-ladder potential, supplemented with laser assisted tunneling, effectively realizes the ground state of one-dimensional hardcore bosons in a discrete lattice [6] with nontrivial hopping phases. We compare observables that are affected by the interactions, such as the momentum distribution, natural orbitals and their occupancies, in the time-dependent continuous system [7], to those of the ground state of the discrete system. Stroboscopically, we find an excellent agreement, indicating that laser assisted tunneling is a viable technique for realizing novel ground states and phases with hard-core one-dimensional Bose gases. Next, we show that, in three-dimensional optical lattices, laser assisted tunneling can be used for realizing a Hamiltonian with Weyl points [3]. Weyl points are synthetic magnetic monopoles that exhibit a robust, three-dimensional linear dispersion, identical to the energy-momentum relation for relativistic Weyl fermions [3], which are not yet discovered in particle physics. Relation to analogous studies in optics will be mentioned [8].
[1] N. Goldman, G. Juzeliunas, P. Ohberg, I. B. Spielman, Rep. Prog. Phys. 77, 126401 (2014). [2] Karlo Lelas, Nikola Drpić, Tena Dubček, Dario Jukić, Robert Pezer, and Hrvoje Buljan, Laser assisted tunneling in a Tonks-Girardeau gas, submitted to New J. of Phys. [3] Tena Dubček, Colin J. Kennedy, Ling Lu, Wolfgang Ketterle, Marin Soljačić, Hrvoje Buljan, Phys. Rev. Lett. 114, 225301 (2015). [4] X. Chen, Z.-C. Gu, Z.-X. Liu, X.-G. Wen, arXiv:1301.0861 [cond-mat.str-el]; Science 338, 1604 (2012). [5] M. Girardeau, J. Math. Phys. 1, 516 (1960). [6] M. Rigol and A. Muramatsu, Phys. Rev. Lett. 93, 230404 (2004). [7] R. Pezer and H. Buljan, Phys. Rev. Lett. 98, 240403 (2007).
[8] Jorge Bravo-Abad, Ling Lu, Liang Fu, Hrvoje Buljan and Marin Soljačić, 2D Mater. 2, 034013 (2015); Tena Dubček, Karlo Lelas, Dario Jukić, Robert Pezer, Marin Soljačić and Hrvoje Buljan, New J. Phys. 17, 125002 (2015).

4. **Yulin Chen** (University of Oxford, UK)
   Visualizing Electronic Structures of Topological Quantum Materials
   Abstract: The discovery of materials with novel properties is one of the most fascinating aspects of physics, and such findings have always played important roles in the development of science and human life. Two recent examples are graphene and topological insulators. Interestingly, both materials possess 2D Dirac fermions; and topological insulators further show distinct topology in their electronic band structures. With the swift development in both fields, two questions have been naturally raised: i). Does there exist a 3D counterpart of graphene, or a "3D graphene"? ii).Besides topological insulators, can one find other materials that have unusual topology in their electronic structures? Remarkably, the answer to both questions can lie on a same type of novel quantum matter – the topological semi-metals - which not only processes 3D Dirac or Weyl fermions in the bulk (in contrast to the 2D Dirac fermions in graphene and topological insulators), but also shows unique surface states result from its non-trivial topology of the bulk electronic structure. In this talk, I will show that by using advanced photoemission spectroscopy with high energy, momentum, and time resolution, we were able to directly visualize the non-trivial electronic structures and unusual dynamics in topological insulators and topological Dirac and Weyl semi-metals recently discovered. Finally, I will briefly discuss the application potentials of these unusual materials.

5. **Shuai Chen** (University of Science and Technology of China, Hefei, China)
   Realization of Two-Dimensional Spin-Orbit Coupling for Bose-Einstein Condensates
   Abstract: Cold atoms with laser-induced spin-orbit (SO) interactions provide intriguing new platforms to explore novel quantum physics beyond natural conditions of solids. Recent experiments demonstrated one-dimensional (1D) SO couplings for bosons and fermions. However, realization of 2D SO interaction for quantum degenerate atom gases, a much more important task, remains very challenging. Here we propose and experimentally realize, for the first time, 2D SO coupling and

topological band for 87Rb degenerate gas through an optical Raman lattice, without phase locking or fine tuning of optical potentials. A controllable crossover between 2D and 1D SO couplings is studied, and the SO effects and nontrivial band topology are observed by measuring the atomic cloud distribution and spin texture in momentum space. Our realization of 2D SO coupling with advantages of small heating and topological stability opens a broad avenue in cold atoms to study exotic quantum phases, including the highly- sought-after topological superfluids.

6. **Cheng Chin** (University of Chicago, USA)
Scaling symmetry of topological defects in quantum critical dynamics
Abstract: Spanning condensed matter, cosmology, and quantum gases, evolution of many-body systems is hypothesized to be universal near a continuous phase transition. A long-sought signature of the universal dynamics is the scaling symmetry of emerging topological defects; examples include cosmic domains in early universe (T. Kibble, 1976), and vortices in quenched superfluid helium (W. Zurek, 1985). We test the scaling symmetry and universality of quantum critical dynamics based on Bose-Einstein condensates of cesium atoms ramping across an effective ferromagnetic quantum phase transition. We observe a sudden growth of quantum fluctuations and domains separated by topological defects (domain walls). Intriguingly, the domains are anti-ferromagnetically ordered with record thermal energy scales as low as kB x 20pK. Time and length scales measured over a wide range of parameters yield precise temporal and spatial critical exponents of 0.50(2) and 0.26(2), respectively, consistent with theory. In the scaled space-time coordinate, correlations collapse to a single curve, in support of the universality hypothesis.

7. **Hong Ding** (Institute of Physics, CAS, Beijing, China)
Observation of Weyl fermions and other exotic fermions in condensed matter
Abstract: In 1929, a German mathematician and physicist Hermann Weyl proposed that a massless solution of the Dirac equation represents a pair of new type of particles, the so-called Weyl fermions. However, their existence in particle physics remains elusive after more than eight decades, e.g., neutrino has been regard-ed as a Weyl fermion in the Standard Model until it was found to have mass. Recently, significant ad-vances in topological materials have provided an alternative way to realize Weyl fermions in condensed matter as an emergent phenomenon. Weyl semimetals are predicted as a class of topological materials that can be regarded as three-dimensional analogs of graphene breaking time reversal or inversion symmetry. Electrons in a Weyl semimetal behave exactly as Weyl fermions, which have many exotic properties, such as chiral anomaly, magnetic monopoles in the crystal momentum space, and open Fermi arcs on the surface. In this talk I will report our experimental discovery of Weyl fermions and other exotic fermions by using angle-resolved photoemission spectroscopy.

8. **Victor Galitski** (University of Maryland, USA)
Soliton motion, dissipation, and death in quantum superfluids
Abstract: Solitons are fascinating non-linear phenomena that occur in a diverse array of classical and quantum systems. In particular, they are known to exist in quantum superfluids, and have been demonstrated experimentally in Bose-Einstein condensates and fermionic superfluids. In this talk, I will first review the general theory of solitons in superfluids and present an exact solution to the problem of a moving soliton in a one-dimensional superconductor. Connections to the inverse scattering method and supersymmetric quantum mechanics will be emphasized. Using these exact methods, the full soliton spectrum will be derived along with its "inertial" and gravitational" masses. The former will be shown to be orders of magnitude larger than the latter. This results in slow motion of the soliton, consistent with recent experiment [T. Yefsah et al., Nature 499, 426, (2013)]. In the second part of my talk, I will discuss the soliton decay and derive the quasiclassical equations of motion containing a non-local in time friction

force. Interestingly, Ohmic friction is absent in the integrable setup and the Markovian approximation gives rise to the Abraham-Lorentz force (i.e., a term proportional to the derivative of the soliton's acceleration), which is known from classical electrodynamics of a charged particle interacting with its own radiation. These Abraham-Lorentz equations famously contain a fundamental causality paradox, where the soliton/particle interacts with excitations/radiation originating from future events. We show, however, that the causality paradox is an artifact of the Markovian approximation, and our exact non-Markovian dissipative equations give rise to physical trajectories. Connections to experiment will be made.

9. **Leonardo Fallani** (University of Florence, Italy)
   Ultracold fermions in synthetic dimensions: gauge fields and chiral edge states
   Abstract: I will report on new directions for quantum simulation with ultracold Fermi gases of two- electron 173Yb atoms. We have engineered Raman transitions between different 173Yb nuclear spin states to synthesize an effective lattice dynamics in a finite-sized "extra dimension", which is encoded in the internal degree of freedom of the atoms [1]. By using this innovative approach, we have realized synthetic magnetic fields for effectively-charged fermions in ladder geometries with a variable number of legs. Direct imaging of the individual legs allowed us to demonstrate the emergence of chiral edge currents and to observe edge-cyclotron orbits propagating along the edges of the system, thus providing a direct evidence of a fundamental feature of quantum Hall physics in ultracold fermionic systems. I will also report on new possibilities opened by the manipulation of the electronic state of 173Yb atoms for the control of interactions and the realization of gauge fields in new synthetic quantum systems [2].
   [1] M. Mancini et al., Science 349, 1510 (2015).
   [2] G. Pagano et al., Phys. Rev. Lett. 115, 265301 (2015).

10. **Mohammad Hafezi** (University of Maryland, USA)
    Topological physics in nanophotonics
    Abstract: Following the measurement of topological invariants in silicon ring resonator systems, we report on the progress of the investigation of non-classical light transport. In particular, we analyze the transport properties of two-photon wavefunctions in a disorders structure with protected topological edge bands, and examine the robustness of quantum transport properties. Moreover, we discuss a design for photonic crystals with topological properties. Both Finite-difference-time-domain simulations and tight-binding model show topological protection as controllable directional light propagation with circularly-polarized dipole excitations and backscattering-free propagation around sharp corners. Such structures can be integrated with nonlinear quantum emitters such as color centers and quantum dots and could be used for robust on-chip quantum information processing and quantum simulation of fractional quantum Hall states. Finally, we discuss the effect of interacting disorder in these systems. Specifically, the possibility that topological ordered states, such as Laughlin states, may be realized in photonic systems has recently attracted a great deal of attention. These states are predicted to arise in strongly nonlinear photonic lattices with artificial gauge fields, where nonlinearities associated with the resonators mimic on-site interactions.

11. **Andreas Hemmerich** (Hamburg University, Germany)
    Observation of chiral superfluid order by matter wave interference
    Abstract: I discuss our recent demonstration of chiral superfluid order for atoms Bose-Einstein condensed in the second Bloch band of an optical lattice. As a key tool we use a matter wave interference technique, which lets us directly observe the phase properties of the superfluid order parameter and allows us to reconstruct the spatial geometry of certain low energy excitations, associated with the formation of domains of different chirality.

12. **Gyu-Boong Jo** (Hong Kong University of Science and Technology)
__Spin-orbit coupled two-electron Fermi gases of ytterbium atoms__
Abstract: Recent development of cooling alkaline-earth-like atoms has led to an increasing potential in utilizing such atoms not only for the study of many-body physics but also for the realization of synthetic spin-orbit coupling in a Fermi gas. In this talk, we first demonstrate the spin-orbit coupling in a two-electron Fermi gas of 173Yb atoms by coupling two hyperfine states in the 1S0 ground-state manifold with the narrow optical transition. We investigate the momentum distribution of the spin-orbit coupled Fermi gas after loading into the lowest-energy dressed state. The momentum asymmetry in the bare spin state is observed and the corresponding momentum distribution is measured for different two-photon detuning. Finally, we will share our on-going effort to implement spin-orbit coupling in various settings as well.

13. **Gregor Jotzu** (ETH, Zurich, Switzerland)
__Floquet-engineering topological and spin-dependent bands with ultracold fermions__
Abstract: Periodically driven quantum systems, when observed on time-scales longer than one modulation period, can be described by effective Floquet Hamiltonians that show qualitatively new features. Using a magnetic field gradient, we apply an oscillating force to ultracold fermions in an optical lattice. The resulting effective energy bands then become spin dependent, allowing for a tunable ratio of the effective mass (including negative values) for each internal state, which can be observed directly. The regime where one spin experiences a flat band and is completely localized whilst the other remains itinerant also becomes accessible. In a honeycomb lattice, circular modulation of the entire lattice potential leads to the appearance of complex next-nearest neighbour tunnelling. This corresponds to a staggered magnetic flux in the lattice, allowing for the realisation of Haldane's model of a topological Chern insulator. The transition between trivial and topologically non-trivial insulating regimes manifests as a gapless spectrum. By simultaneously breaking time-reversal symmetry and the inversion symmetry of the lattice, the transition can be mapped out using Bloch-Zener oscillations. Furthermore, the non-zero overall Berry curvature leads to perpendicular drifts of an accelerated atomic cloud. A crucial question for the extension of Floquet-engineering to interacting systems is whether periodic modulation creates excessive heating in the system. We identify regimes where this heating is minimal which paves the way for studying the interplay of topology and interactions or exotic spin-models. Local spin correlations, which we can measure directly, may give new insights on the nature of the arising phases.

14. **Tin-Lun (Jason) Ho** (Ohio State University, Columbus, USA)
__Fusing of Quantum Hall States in Cold Atoms__
Abstract: TBA

15. Marton Kanasz-Nagy (Harvard University, USA)
__Stabilizing the topological vacuum: Mott skyrmions__
Abstract: The topology of a many-body quantum state can significantly change its excitation spectrum, as has been shown for certain quantum-field theories with topologically non-trivial vacua. In this talk, I will discuss our proposal for an especially stable skyrmion configuration, created in an ultracold nematic superfluid, in which the effect of the skyrmion's topology on its spectrum and quantum numbers can be observed. The underlying Mott skyrmion state is created by loading the condensate into a deep optical lattice, making the center of the trap Mott insulating. This core is surrounded by a superfluid shell, that can naturally host a skyrmion excitation. The resulting skyrmion circumvents the instability problems of earlier skyrmion realizations, thereby allowing to study the topologically non-trivial low energy dynamics of the system.

M. Kanasz-Nagy, B. Dora, E. A. Demler and G. Zarand, Sci. Rep. 5, 7692 (2015).

16. **Wolfgang Ketterle** (MIT, Cambridge, USA)
Spin-Orbit Coupling and Spin Textures in Optical Superlattices
Abstract: A new approach is suggested and demonstrated for realizing spin orbit coupling with ultracold atoms. We use orbital levels in a double well potential as pseudospin states. Two-photon Raman transition between left and right wells induce spin-orbit coupling. This scheme does not require near resonant light, features adjustable interactions by shaping the double well potential, and does not depend on special properties of the atoms. A pseudo-spinor Bose-Einstein condensate spontaneously acquires an antiferromagnetic spin texture which breaks the lattice symmetry similar to a supersolid.

17. **Kam-Tuen Law** (Hong Kong University of Science and Technology)
Ising superconductivity and Majorana fermions in superconducting transition metal dichalcogenides
Abstract: Ising superconductors with in-plane upper critical fields several times higher than the Pauli limits have been discovered recently in transition metal dichacogenides such as MoS2 and NbSe2 thin films [1-3]. These Ising superconductors have very strong Ising spin-orbit couplings (SOC), in the order of 10 to 100meV, which pin electron spins to the out-of-plane directions. This is in contrast to Rashba SOC which pins electron spins to in-plane directions. Here, we explain how Ising SOC can enhance the in-plane upper critical field of Ising superconductors [1-4]. We also show that Ising superconductors can be used to create Majorana fermions by placing a metal wire on top of the Ising superconductor [5], similar to the case of Rashba wire on top of s-wave superconductors. We further show that an applied in-plane magnetic field can drive a monolayer NbSe2 [2,5] and into a nodal topological phase with Majorana flat bands when the applied in-plane field is higher than the Pauli limit but smaller than the upper critical field.
[1] J. M. Lu, O. Zeliuk, I. Leermakers, Noah F. Q. Yuan, U. Zeitler, K. T. Law and J. T. Ye, Science 350, 1353 (2015). [2] X. Xi, Z. Wang, W. Zhao, J-H Park, K. T. Law, H. Berger, L. Forró, J. Shan, K. F. Mak, Nature Physics 12, 139-143 (2016). [3] Y Saito et al. Nature Phyics 12, 144-149 (2016). [4] Benjamin T. Zhou, Noah F.Q. Yuan, Hong-Liang Jiang and K. T. Law, Phys. Rev. B 93, 180501 R (2016). [5] Wen-Yu He, Benjamin T. Zhou, James J. He, Ting Zhang and K. T. Law, arXiv:1604.02867.

18. **Bo Liu** (University of Pittsburgh, USA)
Chiral superfluidity in atomic quantum matter: from center-of-mass p-wave symmetry to Weyl fermions
Abstract: Since the observation of Bose-Einstein condensation and of superfluidity in atomic gases, ultracold quantum gases have become a very versatile tool to explore new quantum states of matter. Because of the highly controllable and clean environment in atomic systems, it is hoped that they will not only provide a perfect simulator of electronic systems, but also opportunities to create new types of quantum states with no counterpart in solids. In this talk, experimentally feasible routes with cold gases based systems to achieve two kinds of new quantum states of matter (i.e., center-of-mass p-wave superfluidity [1] and Weyl superfluids [2]) are proposed.
[1] B. Liu, X. Li, B. Wu and W. V. Liu, Nat. Commun. 5, 5064 (2014).
[2] B. Liu, X. Li, L. Yin and W. V. Liu, Phys. Rev. Lett. 114, 045302 (2015).

19. **Maciej Lewenstein** (ICFO, Barcelona, Spain)
Synthetic and emergent gauge fields in synthetic and real dimensions
Abstract: In my lecture I will report recent progress of ICFO-QOT group in the studies of synthetic and emergent gauge fields in synthetic and real dimensions. I will try to cover 4 subjects: 1) Synthetic gauge fields in synthetic dimensions. After short introduction [1] I will discuss progress toward simulation and characterization of

Quantum Hall Effect in 4D [2]. 2) Anti-ferromagnet in an anisotropic triangular lattice in a trap: does the spin liquid survive? Mean field, exact diagonalization and TNS analyses [3]. 3)Spin chains with loops: Magnetic fluxes in 1D [4]. 4) A toolbox for Abelian lattice gauge theories with synthetic matter [5]. Lattice gauge theory exhibiting novel de-confined and gapless phases.

[1] Synthetic gauge fields in synthetic dimensions, A. Celi, P. Massignan, J. Ruseckas, N. Goldman, I. B. Spielman, G. Juzeliūnas, and M. Lewenstein Phys. Rev. Lett. 112, 043001 (2014). [2] Efficient algorithm for computing the second Chern number in 4-dimensional systems, M. Mochol-Grzelak, A. Dauphin, A. Celi, and M. Lewenstein, arXiv:1407xxxx. [3] Modified spin-wave theory and spin liquid behaviour of cold bosons on an inhomogeneous triangular lattice, Alessio Celi, Tobias Grass, Andrew J. Ferris, Bikash Padhi, David Raventos, Juliette Simonet, Klaus Sengstock, and Maciej Lewenstein, arXiv:1603.06561. [4] Synthetic magnetic fluxes and topological order in one-dimensional spin systems T. Graß, C. Muschik, A. Celi, R. W. Chhajlany, and M. Lewenstein Phys. Rev. A 91, 063612 (2015). [5] Toolbox for Abelian lattice gauge theories with synthetic matter, Omjyoti Dutta, Luca Tagliacozzo, Maciej Lewenstein, and Jakub Zakrzewski, arXiv:1601.03303

20. **Hanns-Christoph Nägerl** (University of Innsbruck, Austria)

Floquet engineering of correlated tunneling in the Bose-Hubbard model with ultracold atoms

Abstract: We report on the experimental implementation of tunable occupation-dependent tunneling in a Bose-Hubbard system of ultracold atoms via time-periodic modulation of the on-site interaction energy. The tunneling rate is inferred from a time-resolved measurement of the lattice site occupation after a quantum quench. We demonstrate coherent control of the tunneling dynamics in the correlated many- body system, including full suppression of tunneling as predicted within the framework of Floquet theory. We find that the tunneling rate explicitly depends on the atom number difference in neighboring lattice sites. Our results may open up ways to realize artificial gauge fields that feature density dependence with ultracold atoms.

21. **Tomoki Ozawa** (University of Trento, Italy)

Quantum Hall effect in momentum space in harmonically trapped topological lattice models

Abstract: In recent years, the study of topologically nontrivial models in ultracold atoms has attracted much interest. Unlike in solid state materials, however, ultracold atomic experiments usually contain an overall harmonic confining potential. One thus usually works with a weak enough confining potential so that its effect can be neglected when exploring topological properties of the model. In this talk, I discuss how such a confining potential can bring new phenomena, making ultracold gases a unique platform to explore topological phenomena beyond what is known from solid state materials. First, I show that harmonically trapped topologically nontrivial models can be mapped onto a particle moving in momentum space feeling the magnetic field in momentum space. The kinetic energy in momentum space is provided by the confining potential in real space, and the magnetic field in momentum space is given by the Berry curvature. Then I discuss how the quantum Hall effect can take place in momentum space. Making use of the fact that the momentum space (Brillouin zone) is a torus, one can directly realize the Niu-Thouless-Wu formalism of quantum Hall effect, where the Hall current is induced by twisting the boundary condition on the torus. I finally explain how such a quantum Hall effect in momentum space can be experimentally probed.

[1] H. M. Price, T. Ozawa, and I. Carusotto, "Artificial magnetic fields in momentum space in spin-orbit-coupled systems", Phys. Rev. Lett. 113, 190403 (2014). [2] T. Ozawa, H. M. Price, and I. Carusotto, "Momentum-space Harper-Hofstadter model", Phys. Rev. A 92, 023609 (2015). [3] T. Ozawa, H. M. Price, and I. Carusotto, "Quantum Hall effect in momentum space", Phys. Rev. B 93, 195201 (2016).

22. **Hannah Price** (University of Trento, Italy)
Extending Synthetic Dimensions for Ultracold Atoms and Photons
Abstract: Synthetic dimensions are emerging as a powerful and general approach for implementing artificial gauge fields and creating topological energy bands for neutral particles. In ultracold gases, motion along a synthetic dimension can be accomplished, for example, through controlled transitions between internal states of atoms [1]. We propose how to extend these ideas also into integrated photonics by exploiting the different modes of a silicon ring resonator as an extra dimension for photons [2]. As we discuss, tunneling along this synthetic dimension can be implemented via an external time-dependent modulation that allows for the simple generation of engineered gauge fields. We then show how such synthetic dimensions in both ultracold gases and photonics can be pushed further to realise the 4D quantum Hall effect for the first time [3]. This sets the stage for the exploration of novel topological phases in higher dimensions.
[1] O.Boada et al., Phys. Rev. Lett. 108, 133001 (2012); A. Celi et al., Phys. Rev. Lett. 112, 043001 (2014); M. Mancini et al., Science 349, 1510 (2015); B. K. Stuhl et al., Science 349, 1514 (2015). [2] T. Ozawa, H. M. Price, N. Goldman, O. Zilberberg, I. Carusotto, Phys. Rev. A 93, 043827 (2016). [3] H. M. Price, O. Zilberberg, T. Ozawa, I. Carusotto, N. Goldman, Phys. Rev. Lett. 115, 195303 (2015).

23. **Mikael Rechtsman** (Penn State University, USA)
Aspects of topological photonics
Abstract: I will introduce photonic topological insulators and discuss a number of recent developments, including robust transport in quasicrystalline systems; non-Hermitian systems with topological states; and protected Majorana-like states in two-dimensional photonic spin Hall systems.

24. **Julius Ruseckas** (Vilnius University, Lithuania)
Spin-orbit coupling for ultracold atoms and for slow light
Abstract: The Rashba-Dresselhaus spin-orbit coupling (SOC) has been widely studied in the condensed matter physics [1]. In the present talk I will discuss methods of producing the SOC for ultracold atoms and slow light. One of the current experimental challenges is to produce a two-dimensional SOC of the Rashba type for ultracold atoms. I will present a novel way of creating the Rashba SOC for ultracold atoms by using a two-component atomic Bose-Einstein condensate confined in a bilayer geometry [2]. The scheme combines an intralayer Raman coupling and an interlayer laser assisted tunneling. An interplay between the two processes gives rise to diverse ground-state configurations for such a bilayer BEC. In the second part I will talk about the SOC for a two-component (spinor) slow light. Such a spinor light has been recently experimentally realized [3]. For creating the spinor slow light an atomic ensemble is coherently driven by two pairs of control laser fields in a double tripod-type setup. The probe fields "dressed" by the atomic medium form quasi-particles - spinor polaritons - that obey under certain conditions a relativistic equation of the Dirac-type [4]. The polaritons posses an "effective speed of light" given by the group-velocity of slow-light, and can be made massive by inducing a small two-photon detuning. If the detuning is due to the atom-atom interaction, correlated pairs of photons can be created [5].
[1] I. Zutic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323-410 (2004). [2] S.-W. Su, S.-C. Gou, Q. Sun, L. Wen, W.-M. Liu, A.-C. Ji, J. Ruseckas, and G. Juzeliūnas, Phys. Rev. A 93, 053630 (2016). [3] M.-J. Lee, J. Ruseckas, Ch.-Y. Lee, V. Kudriašov, K.-F. Chang, H.-W. Cho, G. Juzeliūnas and I. A. Yu, Nat. Commun. 5, 5542 (2014). [4] R. G. Unanyan, J. Otterbach, M. Fleischhauer, J. Ruseckas, V. Kudriašov, and G. Juzeliūnas, Phys. Rev. Lett. 105, 173603 (2010). [5] J. Ruseckas, I. A. Yu and G. Juzeliūnas, arXiv1606.00562.

25. **Jay Sau** (University of Maryland, USA)

Parafermions in atomic gases and the solid state quantum Hall state without superconducting back-scattering

Abstract: Parafermions are generalizations of Majorana fermions that have been predicted to occur at the Interface of superconductors and fractional quantum Hall states. I will start by discussing a recent application of these ideas to potential bosonic quantum Hall systems in ultracold atomic gases[1]. I will then discuss an aspect of the solid state proposal, which makes them experimentally challenging i.e. they require cross Andreev scattering of quasiparticles between counter-propagating edge states of the fractional quantum Hall state. I will describe a theoretical variant on this proposal which eliminates this requirement and is based on superconducting forward scattering alone, which can be generically argued to be present in FQH/SC systems.

26. **Ulrich Schneider** (Max Plank Institute / LMU, Munich, Germany; University of Cambridge, UK)

Interferometric probes of band topology in synthetic quantum matter

Abstract: Topology and geometry are fundamental to our understanding of modern physics, underlying many foundational concepts from high-energy theories, quantum information, and condensed matter physics. In condensed matter systems, a wide range of phenomena stem from the geometry of the band eigenstates, the most prominent examples being the Quantum Hall Effect and Topological Insulators, which are governed by the Berry curvature of isolated bands. For general multi-band systems, the geometry of Hilbert space is encoded in the matrix-valued Wilson line, giving rise to more intricate transport phenomena and holding the potential for holonomic quantum computing.

I will present interferometric measurements of Bloch band geometry using ultracold atoms in optical lattices. In analogy to an Aharonov-Bohm interferometer that measures magnetic flux, we realized an atomic interferometer measuring Berry curvature in momentum space. For our graphene-type hexagonal optical lattice, this interferometer enabled us to directly observe the singular pi-Berry flux localized at each Dirac point.

We furthermore engineered strong-force dynamics in Bloch bands that are described by Wilson lines and observed an evolution in the band populations that directly reveals band geometry. Our techniques enable a full determination of the dispersion relations, band eigenstates, Berry curvature distributions, and topological invariants, including single- and multi-band Chern and Z2 numbers.

27. **Klaus Sengstock** (Hamburg University, Germany)

Experimental reconstruction of the Berry curvature and further topological properties of Floquet engineered optical lattices

Abstract: The Berry curvature is a central property of the topology of a periodic system. The talk will report on the first experimental measurement of the full Berry curvature performed with fermionic quantum gases in a Floquet engineered optical lattices [1] and will discuss future perspective.

[1] Fläschner et al. Science 352, 1091 (2016).

28. **Jonathan Simon** (University of Chicago, USA)

Topological Photonics: Twisted Resonators, Braided Circuits, and Connected Superconducting Coaxes

Abstract: I will present our recent work realizing topological phases of photons. In the optical domain, we employ a non-planar resonator to trap photons on a cone and subject them to a uniform magnetic field. In this context we explore the interplay of geometry and topology, validating the theory of Wen and Zee. In the rf- and microwave- domains, we demonstrate that photons may be trapped in topologically non-trivial lattices; in the RF case, we generate a spin-Hall insulator by braiding the connections between lattice sites. In the microwave case we break time-reversal symmetry by coupling each unit cell to a ferrimagnet, generating a Chern insulator. I

conclude by describing ongoing work to induce strong interactions between photons and build up fractional quantum hall phases of photons.

29. **Sandro Stringari** (University of Trento, Italy)
Superfluidity of a spin-orbit coupled Bose-Einstein condensate
Abstract: In this talk I will discuss various dynamic and superfluid properties characterizing a spinor Bose-Einstein condensed gas in the presence of spin-orbit coupling. The role of the broken symmetries (time-reversal, parity, Galielan invariance) exhibited by such systems and the consequences on the superfluid behavior are explicitly discussed.

30. **Seiji Sugawa** (Joint Quantum Institute, NIST/UMD, USA)
Observation of topological transitions in Abelian and non-Abelian monopole fields
Abstract: Understanding and manipulating the topological properties of physical system is an important topic in contemporary science. Topologically protected quantum control gives robust high-fidelity operation. Quantum Hall system exhibits robust quantum transport with quantized conductance. Singularities - topological defects - in an extended system determine the appearance of the non-trivial topology. We report on the observation of the Abelian Dirac monopole and non-Abelian Yang monopole as singularities in the parameter spaces of the atomic quantum system. We quantified the topological natures of the monopole fields by measuring the 1st and 2nd Chern numbers on manifolds enclosing the monopoles. The Chern numbers were measured by characterizing the local geometric quantity, the (non- Abelian) Berry curvatures, which appears in the linear response of the driven system. By moving the manifolds, we demonstrate topological transitions for each monopole fields, where the topology changes from non-trivial to trivial phases as the monopoles exited the enclosing manifolds. Our realization opens the door for investigating physical phenomena governed by higher gauge symmetry with highly- controllable quantum system.

31. **Masahito Ueda** (University of Tokyo, Japan)
P-wave contact tensor
Abstract: We discuss universal relations in a spinless Fermi gas near p-wave Feshbach resonance and show several universal relations. In particular, we point out that the p-wave contact has the tensor character and discuss its physical consequences.

32. **Hongqi Xu** (Lund University, Sweden)
Topological quantum devices and Majorana fermions in superconductor-semiconductor quantum dot hybrid devices
Abstract: TBA

33. **Jian Wang** (ICQM, Peking University, Beijing, China)
Quantum Griffiths singularity in 2D superconductors and superconductivity in topological materials
Abstract: By both in situ scanning tunneling microscopy/spectroscopy and ex situ transport and magnetization measurements, we find that the two-atomic-layer Ga film with graphene-like structure on wide band-gap semiconductor GaN is superconducting with Tc up to 5.4 K. [1] Furthermore, in three- atomic-layer Ga films, we firstly observe quantum Griffiths singularity in two dimensional (2D) system and superconductors.[2] As for the superconductivity in topological materials, we detect the novel superconductivity in crystalline 3D Dirac semimetal Cd_3As_2 [3] by using point contact measurements with some signatures showing the possibility of topological superconductivity[4].
[1] Physical Review Letters 114, 107003 (2015) (Editors' Suggestion). [2] Science 350, 542 (2015) (with a perspective article: Science 350, 509). [3] Physical Review X 5, 031037 (2015). [4] Nature Materials 15, 38 (2016).

34. **Hong Yao** (Tsinghua University, Beijing, China)
Emergent supersymmetry in topological superconductors and Weyl semimetals
Abstract: Proposed as a fundamental symmetry describing our universe, supersymmetry (SUSY) has not been experimentally discovered in nature so far. Here, we show that SUSY may emerge in low-energy and long-distance physics of certain condensed matter systems such as topological superconductors and Weyl semimetals. By performing sign-problem-free Majorana quantum Monte Carlo simulations of an interacting 2D topological superconductor, we convincingly show that SUSY emerges at its edge quantum critical point (EQCP) of spontaneous time-reversal symmetry-breaking while its bulk is still gapped and topologically nontrivial. Moreover, using renormalization group analysis, we theoretically show that spacetime SUSY emerges at the continuous pair-density-wave transitions in the bulk of 3D ideal Weyl semimetals, which we believe is the first realization of emergent SUSY in 3D systems.

35. **Hui Zhai** (Tsinghua University, Beijing, China)
Toward Holographic Duality in Cold Atom Systems
Abstract: In this talk I will describe recent progress in using out-of-time-ordered correlation function to characterize the chaotic behavior, quantum butterfly effect and the Lyapunov exponent in a quantum system. Based on the holographic duality argument, we conjecture that the Lyapunov exponent defined in this way will peak at the quantum critical point of the Bose-Hubbard model, and we confirm this conjecture by our numerical calculations. We propose how to measure this effect in cold atom experiment and current cold atom setup is well suited to this experiment.

36. **Shizhong Zhang** (The University of Hong Kong)
Universal relations for Fermi gases close to a p-wave resonance
Abstract: In this talk, I discuss recent studies on the universal properties of an interacting Fermi gas close to a p-wave resonance. Compared with the s-wave case, higher partial scattering brings in new features and complications. There are in general more parameters needed for a complete specification of the system properties than that required by the number of scattering parameters (e.g., momentum distribution). Comparison with experiments will be mentioned when appropriate.

37. **Jing Zhang** (Shanxi University, Taiyuan, China)
Experimental realization of a two-dimensional synthetic spin-orbit coupling in ultracold Fermi gases
Abstract: Though significant experimental progresses have been made, a bottleneck in current studies is the lack of a two-dimensional (2D) synthetic SOC, which is crucial for realizing high-dimensional topological matters. Here, we report the experimental realization of 2D SOC in ultracold 40K Fermi gases using three lasers, each of which dresses one atomic hyperfine spin state. Through spin injection radio-frequency (rf) spectroscopy, we probe the spin-resolved energy dispersions of dressed atoms, and observe a highly controllable Dirac point created by the 2D SOC. Our work paves the way for exploring high-dimensional topological matters in ultracold atoms using Raman schemes.

38. **Qi Zhou** (Chinese University of Hong Kong)
Closing band gaps in optical lattices
Abstract: The past a few years have seen exciting developments of using optical lattices to access important topological models and phenomena. Current studies have been mainly focusing on lattices with finite band gaps, in which abelian Berry curvature is sufficient to capture topological properties of the system. In this talk, I will discuss how to engineer optical lattices such that band gaps close due to the requirement of certain crystal symmetries. These optical lattices provide one a unique

platform for studying non-abelian Berry curvatures and the interplay among symmetry, topology and interaction.

39. **Peter Zoller** (University of Innsbruck, Austria)
A 'dark state' optical lattice for cold atoms
Abstract: We describe a novel optical lattice, and thus a novel framework for many-body quantum physics with cold atoms. In contrast to the standard scenario of optical lattices generated by a second order AC Starkshift from an off-resonant standing-wave laser beam, our starting point is 'dark states' in Lambda-type configurations coupling atomic ground states ('spin states') by near-resonant standing-wave Raman beams. This allows us to write a periodic spatial spin-pattern on the atomic wavefunction with sub-wavelength resolution. Our 'dark state' lattice arises from non-adiabatic corrections to this atomic motion. The outstanding feature of our lattice configuration are: the lattice is a periodic array of 'square-well potentials' with structures, which can be tuned on the sub-wavelength scale. We can readily add features to this lattice including a spatially structured spin-orbit couplings. We present a detailed study of the single particle physics in terms of bandstructure. This is based on a multichannel calculation including both 'dark' and 'bright' atomic states in the Lambda-scheme, and we show that spontaneous emission and loss can be made negligible.
Finally, we show that the spatial spin structure inherent in our setup allows us to realize a 'many-body optical lattice', i.e. a situation where there is no (or negligible) single particle optical potential, but instead the atomic interactions are periodically modulated in space with sub-wavelength resolution. As an example, we discuss the formation of 'domain wall molecules' as bound states between two or three atoms induced by modulated dipolar interactions at the interface of spatial regions with different spins. In a broader context we show that this gives rise to unconventional Hubbard models.